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Going with the flow: Hydrologic response of middle Lena River (Siberia) to the climate variability and change

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ABSTRACT

Recent observations indicate that over the last decades, climate change has increasingly influenced the frequency, intensity and duration of extreme climatic and hydrologic events. The main aim of this study is to determine the hydrologic response, especially the flood evolution, of the Lena River in Eastern Siberia to ongoing climate change. Draining the coldest region of the Northern Hemisphere, the Lena River is impacted by global warming, which is particularly pronounced in periglacial areas characterized by deep and continuous permafrost. We document the hydrologic variability of the Middle Lena River, first by characterizing trend and stationarity of monthly discharges. Second, we analyze on the basis of the peak over threshold method (POT) the temporal evolution of intensity and duration of three discharge classes: bar-full discharge, bank-full discharge and large floods. Finally, we also determined the dates of the flood beginning and of the flood peak. Data on mean monthly discharge and flood peaks are available since 1936 and daily discharges since 1954. Our results provide evidence for a net hydrologic change with an increase in the intensity and duration of floods in the two decades ending in 2012. The frequency of high floods is unprecedented, and small floods no longer occur. The tail of the temporal distribution of the flood peak is also changing. More frequent early floods are occurring in spring with secondary flood peaks in summer, the latest probably represents the most striking change. Furthermore, the changes have been accelerating since 2004. Finally, two islands were instrumented (2008–2012) in order to study the flooding dynamics with a better precision.

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1. Introduction

Numerous publications recently reported important hydrologic changes in Arctic and sub-Arctic rivers related to climate change (Bennett et al., 2015; Berezovskaya et al., 2005; Déry et al., 2009; Déry and Wood, 2005; Peterson et al., 2002; Serreze et al., 2002; Shiklomanov et al., 2007; Woo et al., 2008; Ye et al., 2009; Walvoord and Kurylyk, 2016). Arctic hydrologic cycles are intensifying due to the increase in air temperature and atmospheric moisture and hence in precipitation (Fedorov et al., 2014; Fukutomi et al., 2004; Iijima et al., 2016; Yang et al., 2002; Zhang et al., 2012). Increasing solid precipitation in winter is also well documented over northern Europe and Asia (Bring and Destouni, 2013; Bulygina et al., 2009; Rawlins et al., 2009; Stieglitz et al., 2003; Tan et al., 2011; Watson et al., 2013; Yang et al., 2002), and winter and/or spring runoff have been shown to be positively correlated with winter precipitation over extensive regions in the Arctic. Snowmelt on frozen ground together with earlier thawing tends to increase runoff rather than infiltration (Berezovskaya et al., 2005; Brabets and Walvoord, 2009; Peterson et al., 2002; Rawlins et al., 2009; Watson et al., 2013; Yang et al., 2004; Ye et al., 2009). Future projections suggest that an earlier 0 °C isotherm in spring will have a major impact on the water discharge of large Arctic rivers in the 2050 s (Prowse et al., 2010). Recent studies highlight the enhancement of poleward moisture transport and storm activity in summer (Iijima et al., 2016; Wu et al., 2016; Zhang et al., 2012).

In the coldest Arctic regions, the fluvial regime of periglacial hydrosystems depends to a great extent on permafrost characteristics: the extent, temperature, and depth of the active layer, the

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contribution of underground water and talik, etc. (Beltaos, 2000; Osterkamp, 2005, 2; Rowland et al., 2010; Woo et al., 2008; Ye et al., 2009). Over the course of the year, the Arctic fluvial regime combines a long low water stage in winter – because of the limited contribution of underground water – and brief (and often brutal) flooding in spring, both features depending on interactions between the permafrost and the temperature. Permafrost areas are very sensitive to warming. In Alaska, the warming average was around 1 °C, but reached 3–4 °C in the Arctic Coastal Plain (Osterkamp, 2005). In Eastern Siberia, permafrost temperature already underwent an increase up to 1 °C over the course of the 20th century (Fedorov and Konstantinov, 2003) and an increase in warming has been observed since the beginning of the 21st century (Fedorov et al., 2014). In the Lena Basin, an increase up to 4 °C is projected for the period 2040–2069 under the warm (wet) A2 scenario (Bring and Destouni, 2013).

A general long-term increase in mean annual discharge has been observed in many Siberian rivers, including the Lena River (Shiklomanov et al., 2006). As many long Arctic and sub-Arctic hydrosystems are oriented South-North, they are affected by different climatic influences: the contribution of the snowmelt water decreases downstream and the influence of the permafrost and its associated active layer takes over. In the 1960–2001 period, N. Kichigina (2013) examined the hydrological changes in the upper basin of the Lena River before and after the climate change (1960–1979 and 1980–2005), and reported intra-annual redistribution of runoff (Kichigina, 2013). As the regime is dominated by the supply of snowmelt water, the upper Lena River is witnessing a marked increase in winter, because of less freezing and early snowmelt. Downstream, in Eastern Siberia, the middle Lena River reflects the influence of its upper basin, but also the strong influence of the deep continuous permafrost and the seasonal thawing of the active layer. In Yakutia, permafrost covers more than 80% of the area and it is an ice-rich permafrost (40–80% of ice content) (Soloviev, 1973). Consequently, the monthly ratio of maximum to minimum water discharge increases downstream, correlated with the permafrost cover of the basin (Ye et al., 2009). Since the 1980s, there has been actually a moderate increase in the mean annual discharge of the middle Lena River (+3%), but the supply of water increased markedly at the end of winter and in early spring (+22–23% in March and April) (Gautier et al. 2008; Yang et al., 2002). The 10% increase in downstream Lena River discharge from 1936 to 2001 was mainly due to large-scale atmospheric change and to the impact of the large dams built on a major tributary (Viliuy R.) of the lower Lena River (Berezovskaya et al., 2005). The temperature of the Lena River also directly reflects the temperature of the air, and the temperature of the stream has been much warmer since the 1980 s than before (+3.23 °C in July, +1.72 °C in June and + 1.05 °C in May (Costard et al., 2007).

The fluvial regime of the Arctic rivers is immoderate with very low flow during winter and a spring flood characterized by a steep rising limb and a peak discharge that can exceed by ten times the winter discharge. Because of their South-North course, the flood wave generated by the snowmelt in the upper basin arrives in still frozen areas, creating a specific river process called river outburst. The outburst causes a very rapid rise in water level, with the dislocation of the river ice cover on the river during the winter. Flooding, ice jams and brutal ice breaks are common features of the breakup, even if their intensity varies greatly. Costard et al. (2014) distinguished two main phases during the spring flood: (i) the breakup *sensu stricto* of the ice cover with subsequent ice jams that usually correspond to the rising limb of the hydrograph and (ii) overbank flooding following the sudden rise in the water level. The extreme hydrologic events vary with natural climatic variability, large-scale atmospheric changes causing wet and dry cycles on Artic rivers (Berezovskaya et al., 2005). However, Shiklomanov et al. (2007) compiled data on daily river discharge from 139 gauging stations distributed across the Russian Arctic, examined spring maximum discharge and found no widespread significant change in spring maximum discharge, except for the Lena River, which showed a general positive trend between 1940 and 2001. However, identifying the factors that drive hydrologic changes in these very large basins remains challenging.

Recently Bennett et al. (2015) underlined "the lack of long-term, high quality, continuous records of streamflow available for in-depth analysis" (Bennett et al., 2015). For this reason, we aim to detail the hydrologic reaction of the Lena River to global warming since the first part of the 20th century. More precisely, the present paper examines changes in water discharges and flood events in the middle Lena River in Eastern Siberia. Water discharge data are compiled for a period of 76 years. With longer time series (1936–2012) than the previous studies (Yang et al. 2002; Peterson et al., 2002; Shiklomanov and Lammers, 2009), we are able to analyze long-term changes and focus on very recent changes. The analysis of daily and monthly discharge helps define important hydrologic changes that could have a major impact on the river bed. We describe changes in flooding in terms of the date, the duration and the intensity of hydrologic events. We examine three discharge thresholds: bar-full level, bank-full level and large floods and investigated the intensity, duration and distribution of these discharges over time. The precise flooding process is also analyzed on two instrumented islands (2008 – 2012).

2. Study area

The Lena River is one of the longest rivers in the Arctic. It is 4.400 km long and drains a 2.49 10^6 km^2 basin (at Kusur station). In terms of discharge, the Lena River is the second biggest supplier of water to the Arctic oceans with 525–257 km^3 per year, just after the Yenisei River (581–603 km^3) and well before the Mackenzie (333 km^3) (Antonov, 1960; Gordeev and Sidorov, 1993; Shiklomanov et al., 2006).

Our study area is located in the upper part of the middle Lena River, near Yakutsk (62°01′37″N; 129°43′57″E, Fig. 1), where the active floodplain widens after a long course through a narrow valley (Fig. 1A). The river takes on a multiple-channel pattern (Fig. 1), with numerous channels surrounding large barren sand bars and islands entirely covered by a willow forest (Gautier and Costard, 2000; Costard et al., 2014).

Our field observations lasted from 2008 to 2012 (Program Agence Nationale de la Recherche *ClimaFlu*), the aim was to quantify erosion and sedimentation on river islands. The two islands that were instrumented and surveyed (2008 – 2012) are located upstream (Eselyakh 12 km and Timochka 5 km upstream) of Tabaga gauging station (Fig. 1A). The islands themselves are composed of fluvial deposits colonized by perennial alluvial vegetation.

3. Data and methods

3.1. Hydrologic data

The study combined different approaches. The first was the analysis of monthly and daily hydrologic data.

Water discharge data were compiled for 76 years at Tabaga gauging site (61°47′38.48″N; 129°40′4.70″E, Fig. 1), which is located at the beginning of the middle Lena floodplain, and drains the upper Lena basin (897,000 km^2). The Tabaga site represents the influences of a quasi-pristine basin, without large dam in its upper reach, which is why we preferred Tabaga over Kusur station, where the influence of the large dams installed on the Viliuy River can be detected. We analyzed the Hydrologic Year Books (available at the

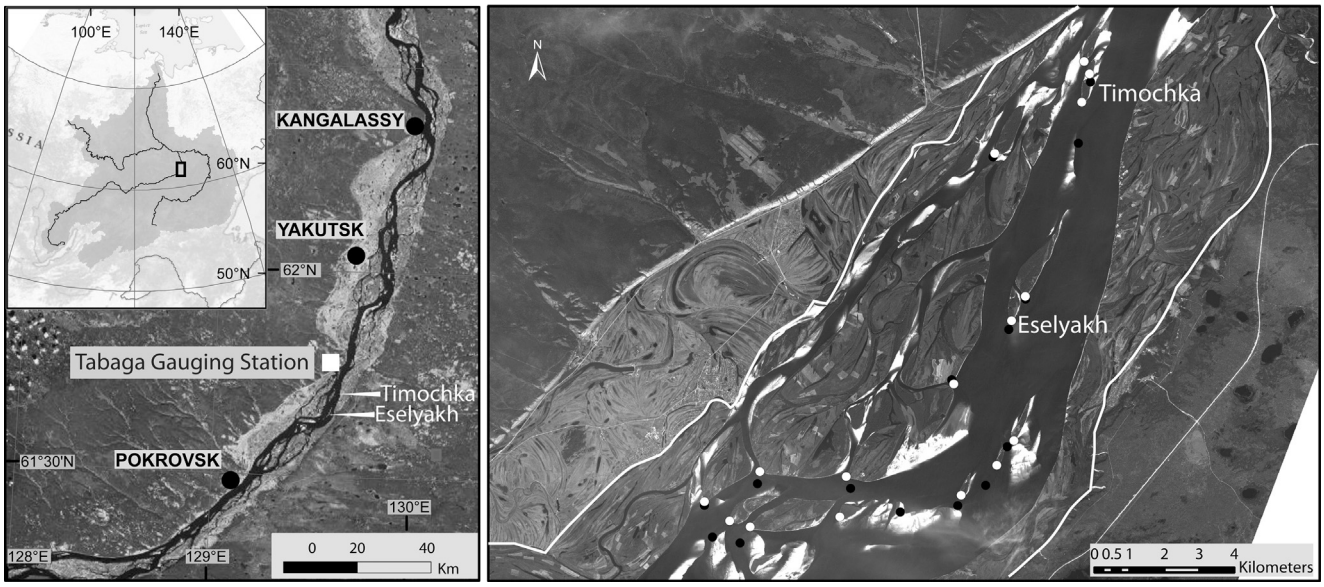

Fig. 1. Map of the study area. A. The middle Lena River valley from Pokrovsk to Kangalassy; B. Zoom on two islands. White line: limit of the active floodplain; white point: island head in 1980; black point: island head in 2008. Back-ground image: Spot Image 2008.

Permafrost Institute at Yakutsk) for the 1937–2012 period. Mean monthly discharge and the maximum stage are available since 1937. Daily discharges are also available since 1954. We reconstructed maximum water discharges on the basis of a rating curve for the period 1937–1954. According to a previous precise study of water discharge uncertainty in cold regions (Shiklomanov et al., 2006), the greatest error in daily discharge is observed during winter, because of the ice cover. So, large uncertainties are calculated during low-water stage (varying between ±5% and ±25%). For the Lena River at Kusur, the error represents ± 20% during the minimal water stage period (winter) and ±4–5% during the high water stage (spring and summer) (Shiklomanov et al., 2006). For this reason, the Russian hydrologic survey calculates a correction coefficient for the discharge on rivers that have a stable ice cover during the winter. Thus, the same uncertainty can be assumed for Tabaga gauging station.

3.2. Multi-decadal analysis of water discharge

First, we calculated the mean monthly discharge, particularly for the spring and summer seasons (May-September). We used long term trend analysis to identify changes and the Mann-Kendall test to determine the statistical significance of the changes. We also used the Pettitt test, a non-parametric one, performed for testing the null hypothesis that there is no break in a series, against the alternative that a stepwise shift in the mean is present. Second, we focused on the high water level and the flooding period with an appropriate peak-over-threshold (POT) method (also called partial duration series) on daily discharges (May-September). The peak over threshold method, developed by Lang et al. (1999) can be adapted to different environments (Dépret et al., 2015; Gob et al., 2016; Gu et al., 2016) and enables the determination of flood maxima and the calculation of flood duration. The method consists of retaining the discharge peaks that exceed a given threshold (or "base level") thereby enabling a "more rational selection of events to be considered as *floods*" (Lang et al., 1999: 103). The first step is to check if two successive events are separated or not. Two events are identified if they are separated by at least five days plus the natural logarithm of the basin area (in miles^2) (*i.e.* 18 days for the Lena River at Tabaga gauging site: 5 + ln(346333.6 mi^2)), or if the discharge between the two peaks drops below 75% of the lowest of the two peaks. To select threshold levels, we used an approach based on the identification of different water levels in the river. The thresholds were determined based on our *in-situ* observations during the study years and according to data from the Hydrologic Survey of the Sakha Republic. The first discharge, with 20,000 m^3 s^{-1}, corresponds to the submersion of the entire width of the active bed (composed of all active channels and barren sandy bars), which is considered as a "bar-full discharge". According to the study conducted by Biedenharn and Thorne (1994) on the Mississippi River, the bar-full stage has a geomorphic effect on the river bed, by transporting a large load of sediment (Biedenharn and Thorne, 1994). Second, the discharge of 30,000 m^3 s^{-1} corresponds to the mean bank-full discharge for the study reach. The Hydrologic Survey of the Sakha Republic considers that population alerts about flooding should begin at 8 m at Tabaga, a level that corresponds to approximately 31,000–32,000 m^3 s^{-1}. The third discharge threshold – 40,000 m^3 s^{-1} (*i.e.* a height of 9 m at Yakutsk) is considered as a major flood. Hence, the three discharge classes analyzed were (i) between 20,000 and 30,000 m^3 s^{-1}, (ii) between 30,000 and 40,000 m^3 s^{-1} and (iii) above 40,000 m^3 s^{-1}. The duration was measured based on the number of days in a given discharge class.

Two dates in the hydrologic year were also examined: the first day of bar-full level in spring, considering that it expresses the beginning of the flood season, and the date of the peak flow.

3.3. Analysis of the in situ flooding process (2008 – 2012)

It was not possible to make direct measurements on floodplain and islands during floods. Thus, two islands (Timochka and Eselyakh, Fig. 1) were equipped (2008–2012):

i) First, flood duration and water height were directly measured on the two islands with temperature sensors (thermo-buttons, 0.5 °C accuracy, ProgesPlus, Willems, France). The thermo-buttons were installed on different trees, at 0.5 m intervals from the soil surface to a height of 4 m; the temperature was recorded at 3 hourly intervals from the end of April until October (Fig. 2). Comparing the

Fig. 2. Water level sensors on islands (Timochka and Eselyakh). Thermo buttons register temperature of the air and/or temperature of the water every 3 h. They are installed every 0.5 m on trees.

temperature measured by the buttons with the temperature of the river water and with the air temperature made it possible to determine the level of submersion. When the inundation occurs, the temperature of the lowest submerged button (0.5 m) suddenly changes and differs from the upper thermo-buttons that are not inundated. The upper button (1m) that can be submerged few hours after will show the same evolution. By that mean, it is possible to have a good appreciation of the water height on islands (with a 50 cm uncertainty) during the flooding. The data were of course compared with the discharge data provided by Tabaga gauging station.

ii) Since water temperature plays an important role in the thermal erosion of the frozen banks, temperature data are also analyzed and compared for each flood.

The detailed timing of the flood on the Lena River was also recorded each year from a relatively high terrace in the Lena floodplain using wide angle and high resolution optical instruments (every spring from 2008 to 2013). Photographs were taken to evaluate the level of ice and water on the two islands (Costard et al., 2014).

4. Results

4.1. Major increase in mean annual and monthly discharge

The hydrograph of the middle Lena River is highly representative of a periglacial and high-latitude continental area, where permafrost plays a major role. The main annual hydrologic features since 1937 are listed in Table 1 and mean monthly discharge per decade is shown in Fig. 3. With a low mean annual discharge (around 7200 $m^3 s^{-1}$ at Tabaga), the Lena River has a weak specific discharge: 7–8 L s^{-1} km^{-2}, reflecting the low contribution of underground water. From October to the end of April, the river goes through a long low water stage, and is covered by ice between 200 and 250 days (Fig. 3). The hydrologic year is dominated by rapid flooding and breakup that occurs around the middle of May. The rising limb of the flood is most of the time very steep. Discharge can be multiplied by a factor of 10 in a single day; the flood peak sometimes reaches 40,000–50,000 $m^3 s^{-1}$ at Tabaga. The flood wave coming from the upper part of the basin located in the Prebaïkal Mountains propagates across the floodplain and active channels that are still frozen. The flood wave arrives in Eastern Siberia between May 15th and May 30th. The breakup and subsequent overbank flooding are highly variable. In May, the initial breakup of the ice cover on the river, which can be very short and brutal, is followed by overbank flooding. More rarely, the rising limb is gentler because of a progressive arrival of the upstream flood. The water level drops from July to October, with a plateau in August and September due to late summer storms. A secondary peak, created by intense rainfall, can occur in summer.

The mean annual discharge for the whole 1936–2012 period was around 7200 $m^3 s^{-1}$ (7210 $m^3 s^{-1}$ for 1936–2012 and 7212 $m^3 s^{-1}$ for 1960–1990, the standard period), it increased by 22.7% after 2004 (*i.e.* a mean discharge of 8846 $m^3 s^{-1}$ for the 2005–2012 period). From 2006 to 2009, the average annual discharge exceeded 9200 $m^3 s^{-1}$. Records for 1983 and 2012 showed a mean annual discharge of 10,500 and 10,200 $m^3 s^{-1}$ respectively (Table 1).

Mean monthly discharges have increased significantly in recent decades (Fig. 3). The Mann-Kendall test revealed a positive tendency for several months in winter (November to January) and in summer (June and September) (p-value < 5%). Winter and spring discharges were characterized by a significant increase after the late 1980 s, especially at the end of winter and spring (+21.4 and + 16.6% in May and June, respectively). For example, the mean discharge in May increased significantly (Pettitt's test) after 1995. Positive anomalies were recorded for monthly discharge in May; except 2003 & 2004, every year since 1996 was positive. From the end of spring to the end of summer, hydrologic changes were less pronounced (+4–+8.7%).

The reinforced trend was quite clear in the last period (2006–2012, Fig. 3): after 2006, the mean annual discharge was 31% higher than in the previous period. This increase was mainly due to the increase in April and May (+44.7 and +43.8% respectively), and in late summer and autumn (August to October: +22 to +33%). The monthly discharge in the last period is easy to distinguish from the previous periods (*i.e.* before 2006), as it was above the other periods in almost all the months (Fig. 3).

The recent hydrologic change is also reflected in the increased frequency of positive anomalies. One period of positive anomalies is observed from 1958 to 1963. However, 14 positive anomalies

Table 1
Main hydrologic features of the Lena River at Tabaga gauging station (1936 – 2012).

Year	Mean Annual Discharge $m^3 s^{-1}$	Flood Peak			Durations (N Days)			Secondary Peaks			
		Discharge $m^3 s^{-1}$	Date	Type	20,000 < Qw < 30,000 $m^3 s^{-1}$	30,000 < Qw < 40,000 $m^3 s^{-1}$	Qw > 40,000 $m^3 s^{-1}$	Qw > 20,000 $m^3 s^{-1}$	Date	Duration Ndays	Main Origin
1936	7246										
1937	7845	*37,008*	May 22								
1938	8342	*34,869*	May 23								
1939	5438	*26,646*	May 20								
1940	5371	*38,196*	May 27								
1941	5951	*36,485*	May 26								
1942	5988	*45,991*	May 26								
1943	5404	*36,960*	May 8								
1944	6499	*33,586*	May 22								
1945	6646	*34,679*	May 17								
1946	6914	*40,573*	May 31								
1947	6070	*30,687*	May 18								
1948	6661	*25,648*	May 12								
1949	8607	*41,666*	May 19								
1950	5654	*34,631*	May 27								
1951	7047	*30,401*	May 24								
1952	6722	*37,056*	May 21								
1953	5424	*34,631*	May 21								
1954	5027	29,500	June 14	P	29	0	0				
1955	6697	52,700	May 22	R	34	3	4				
1956	7568	39,900	May 30	R	7	29	0				
1957	7410	33,900	May 24	R	32	10	0				
1958	8278	46,700	May 25	R	30	13	8				
1959	8968	43,200	June 12	P	22	21	12	25,400	Sept. 6	12	Local
1960	7615	44,100	May 30	R	13	16	3	20,000	Sept 1	2	Local
1961	7851	34,000	June 6	P	32	21	0				
1962	8509	49,700	May 23	R	39	29	4				
1963	7569	36,200	June 30	P	20	28	0				
1964	6650	42,500	May 27	R	30	8	2				
1965	5909	26,100	June 18	P	25	0	0				
1966	7071	47,800	May 22								
1967	7378	36,200	May 13	R	19	4	0	25,100	Aug. 18	2	Upstream
1968	6223	35,100	May 16	R	29	2	0				
1969	5705	31,900	June 1	R	30	3	0				
1970	6793	33,700	June 3	R	31	11	0	21,700	Sept. 16	4	Upstream
1971	7731	39,200	May 19	R	35	6	0	21,200	Sept. 13	5	Upstream
1972	5602	27,700	May 26	R	12	0	0				
1973	6732	32,900	May 24	R	43	1	0	25,200	Aug. 5	16	Upstream
1974	7100	*37,530*	June 16								
1975	6748	28,400	May 17	R	29	0	0				
1976	6783	31,400	June 20	P	38	3	0				
1977	6950	31,200	June 9	P	43	3	0				
1978	8570	37,500	June 17	R	37	27	0				
1979	6939	38,000	May 28	R	10	13	0				
1980	7093	32,000	June 17	P	40	7	0				
1981	8425	31,900	June 27	R	49	9	0	33,600	Sept. 2	25	Upstream
1982	8463	36,800	June 15	P	34	24	0				
1983	10,511	37,400	June 11	P	44	39	0	27,600/ 22,600	Aug. & Sept.	21	Local
1984	8027	43,700	May 21	R	18	24	4				
1985	5543	28,100	June 22	P	30	0	0				
1986	5164	29,600	June 8	P	34	0	0				
1987	5610	31,900	June 2	R	23	6	0				
1988	8991	34,800	July 10	P	82	7	0	27,900	Aug. 7	27	Upstream
1989	8118	35,600	June 7	P	39	16	0				
1990	5803	26,900	May 19	R	20	0	0				
1991	5812	39,400	May 24	R	16	4	0				
1992	7413	45,100	May 31	R	6	8	8				
1993	5584	27,800	May 28	P	28	0	0				
1994	7708	40,600	June 11	P	22	17	2				
1995	6529	37,300	June 17	P	24	12	0				
1996	7025	34,900	May 24	R	40	12	0				
1997	8379	28,800	May 26	P	46	0	0	25,500	Aug. 2	5	Upstream
1998	8699	36,100	July 2	P	40	23	0	24,400	Aug. 12	8	Upstream
1999	6540	45,800	May 23	R	9	10	4				
2000	8354	35,000	May 17	R	41	8	0	25,900	Aug. 1	4	Upstream
2001	6528	44,500	May 24	R	12	10	4				
2002	7222	36,700	May 22	R	12	18	0				
2003	5939	31,500	May 28	R	11	2	0				

(*continued on next page*)

Table 1 (*continued*)

Year	Mean Annual Discharge $m^3 s^{-1}$	Flood Peak			Durations (N Days)			Secondary Peaks			
		Discharge $m^3 s^{-1}$	Date	Type	20,000 < Qw < 30,000 $m^3 s^{-1}$	30,000 < Qw < 40,000 $m^3 s^{-1}$	Qw > 40,000 $m^3 s^{-1}$	Qw > 20,000 $m^3 s^{-1}$	Date	Duration Ndays	Main Origin
2004	8507	42,700	June 18	P	29	11	9	23,500	Aug. 6	6	Upstream
2005	7798	31,300	June 14	P	57	4	0				
2006	9820	49,600	June 11	P	12	18	21	21,000	Aug. 24	5	Local
2007	9253	40,200	May 15	R	22	35	1				
2008	9525	36,900	May 20	R	47	11	0	36,700	Sept. 8	16	Upstream
2009	9722	37,000	June 14	P	20	25	0	20,100	Sept. 19	1	Upstream
2010	7318	51,600	May 20	R	13	5	4				
2011	7467	45,000	May 16	R	24	3	3	34,300	Aug. 9	10	Upstream
2012	10,205	44,700	May 20	R	43	28	8	38,400	Aug. 3	8	Upstream

In italic: reconstructed discharge; Type: R: rapid increase of the flood; P: progressive rising of the water level. For secondary peak, main origin: i) upstream: secondary peak triggered by a flood wave coming from the upper basin; ii) local: flood triggered by a local rainfall.

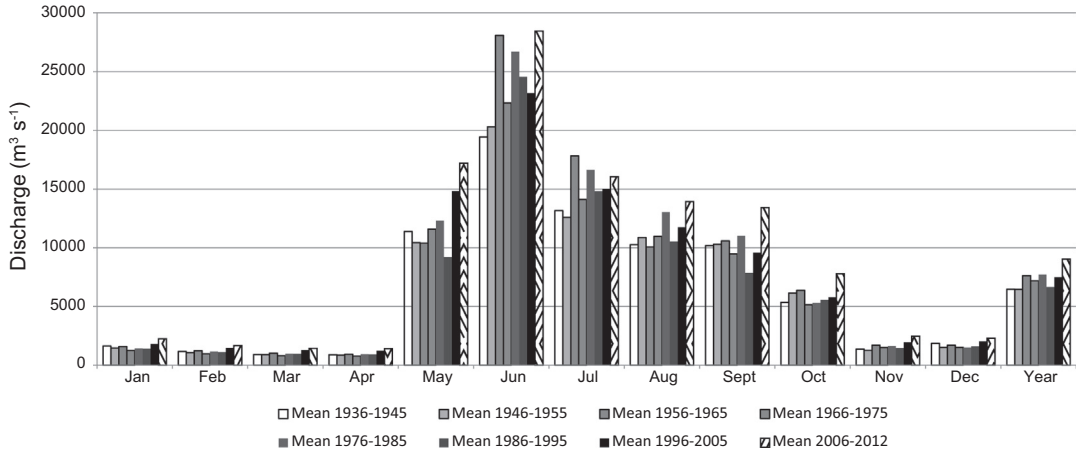

Fig. 3. Mean monthly discharges ($m^3 s^{-1}$) per decade of the Lena River at Tabaga gauging station (1936–2012).

were recorded in the 20 years preceding 2012 and there was one positive anomaly every year after 2006 (Fig. 4). Furthermore, very marked positive anomalies were recorded, exceeding 130%, a value that was not registered between 1936 and 1982.

4.2. Changes in the flooding regime

4.2.1. Recent changes in flood peaks

The great majority of flood peaks occurs in May and June, associated with the flood wave coming from the upper basin and with the local break-up. The floods present generally a steep rising limb (type "R" for rapid, Table 1) and more rarely a progressive flood rising limb (type "P", Table 1). A steep rising limb generally implies a brutal break-up and a flood peak in May (but it does not necessarily imply a high magnitude event). A progressive flooding generally causes a flood peak in June. Secondary peaks may be registered in summer, their origin is different: they are triggered by rainstorms. In the 1954–2012 period for which daily data were available, the POT method helped identify 90 peaks, *i.e.* a mean value of 1.55 events exceeding 20,000 $m^3 s^{-1}$ per year. Indeed, one or two peaks

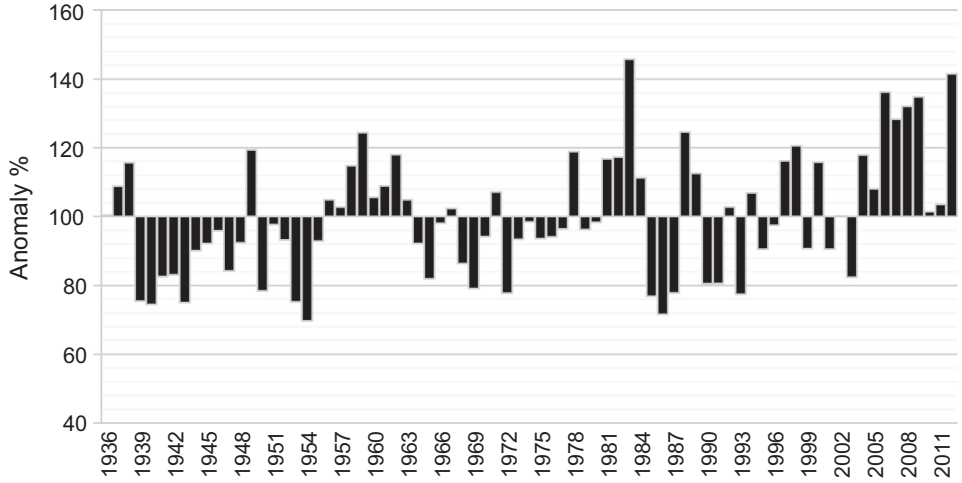

Fig. 4. Anomalies in the mean annual discharge at Tabaga gauging site (100: mean value 1936–2012).

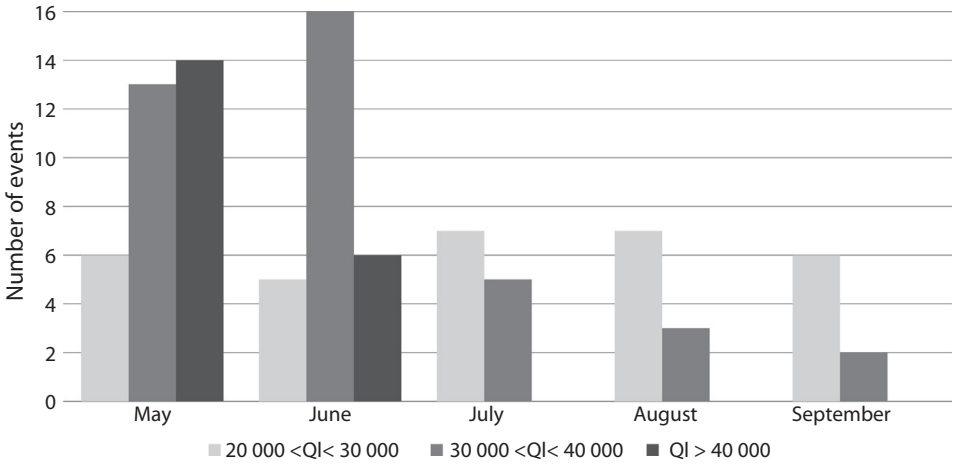

Fig. 5. Monthly distribution of the three discharge classes (1954–2012; $m^3 s^{-1}$).

were usually recorded in the same spring or summer. In 1981 and in 2012, four flood peaks were recorded, and since 2004, at least two peaks occurred every year.

Together, May and June accounted for the highest discharges: 20 peaks exceeding 40,000 $m^3 s^{-1}$ were recorded at Tabaga gauging site between 1954 and 2012 (Table 1; Fig. 5). The highest floods generally occurred in May (14 events), and were rarer in June (Fig. 5). The 29 peaks of between 30,000 and 40,000 $m^3 s^{-1}$ were more frequent in June (16 peaks in June and 13 peaks in May), but they were less frequent in the summer (10 events distributed in July, August and September, Fig. 5). These summer overbank flows were as good as absent before 1981 (only one flood in July 1958). Bar-full discharges (between 20,000 and 30,000 $m^3 s^{-1}$) occurred from May to September with a maximum occurrence in July and August (with 14 events between 1954 and 2012) (Fig. 5).

The river showed high inter-annual variability in terms of floods and the annual maximum ranged from 20,000 to more than 50,000 $m^3 s^{-1}$. Two historic floods occurred, one on May 22, 1955 (52,700 $m^3 s^{-1}$) and the other on May 20, 2010 with 51,600 $m^3 s^{-1}$ (Table 1). The 2010 flood was catastrophic in the area of Yakutsk, where many inhabitants had to be evacuated.

Two periods were characterized by frequent high floods. First, the 1957–1966 period was an "active" period with several high floods (frequency = 0.6, six events exceeding 40,000 $m^3 s^{-1}$ year). This was also an abundant hydrologic period in terms of mean annual and monthly discharge (Fig. 3 and Fig. 4). Second, after the 1980s, the frequency of floods greater than 40,000 $m^3 s^{-1}$ increased progressively (Fig. 6), whereas "normal" floods were less frequent. In the last years leading up to 2012, an unprecedented frequency of high floods was recorded, whereas "small" events (between 20,000 and 30,000 $m^3 s^{-1}$) no longer occurred. The period between 1967 and 1986 was relatively "calm" with only one high flood. This corresponded to a dry period in terms of average annual discharge with a majority of negative anomalies (Fig. 4).

4.2.2. The duration of the three discharge classes

Hydrologic changes can also be detected by analyzing the duration of the different classes of discharge. Reflecting the general immoderation of the river, the duration was also subject to great inter-annual variability (Fig. 7). The first discharge class (20,000–30,000 $m^3 s^{-1}$) lasted from a few days (12–13 days in 1972 and 2003, for example) up to three months (1988, for example). The mean annual duration of this class represented a minimum value for the period 1954–1963 (26 days), further evidence for the dry period. The longest durations were recorded in 1988 (82 days) and in 2005 (57 days) of bar-full level.

The two classes of floods (*i.e.* above 30,000 $m^3 s^{-1}$) varied greatly. The mean duration of overbank discharge (30,000–40,000 $m^3 s^{-1}$) ranged from zero days to more than 20 days per year. The "abundant" decade (mid-1950s to mid-1960s) was marked

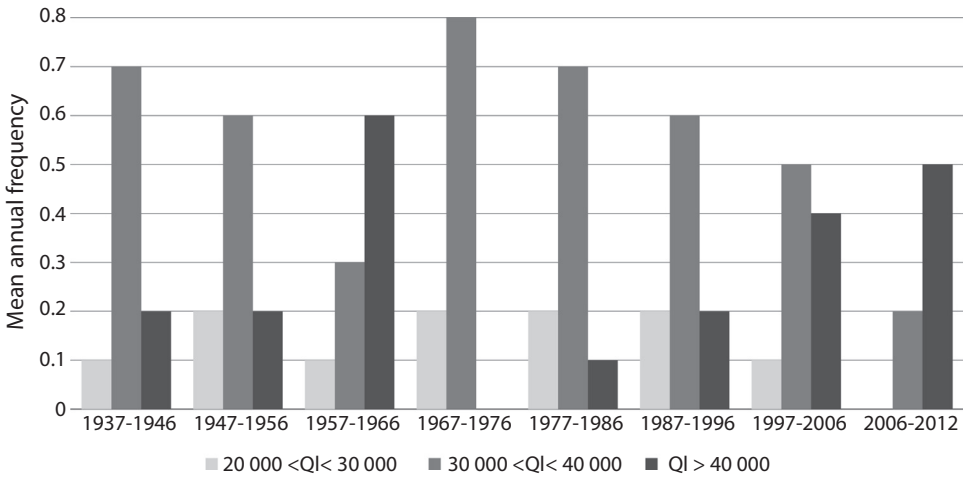

Fig. 6. Mean annual frequency of maximum water discharge (per decade between 1937 and 2012).

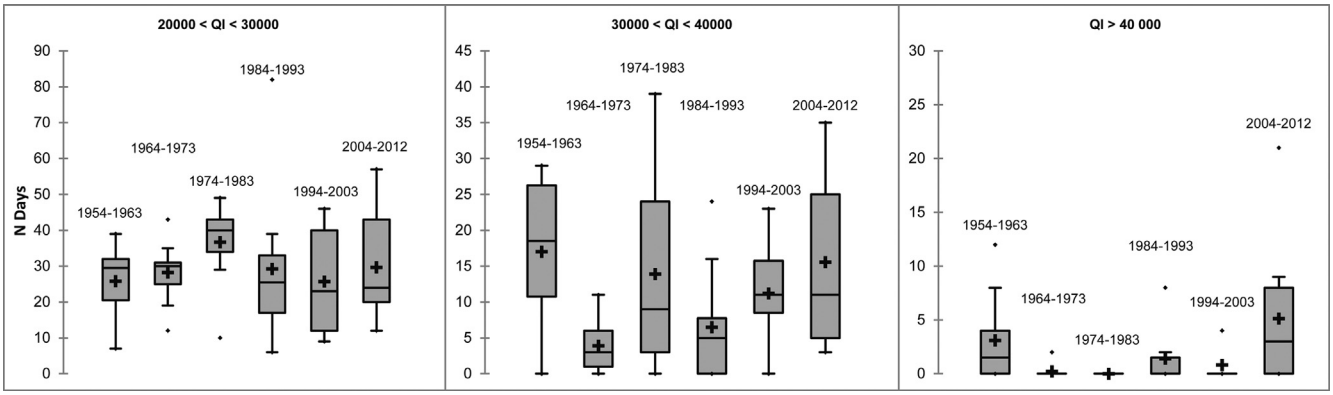

Fig. 7. Duration in days of the three water discharge classes (per decade, 1954–2012). Cross: mean value; box: median, 1st and 3rd quartile; dots: maximum and minimum values.

by long flood durations: 17 days per year on average. However, after the 1990s, the duration progressively increased. The longest floods were recorded after 2004: 16 day between 30,000 and 40,000 $m^3 s^{-1}$ for the 2004–2012 period and more than 5 days for the greatest floods (Fig. 7). As a consequence, by cumulating the two flooding classes, the mean annual duration of flooding was actually 21 days after 2004, contrasting with a dozen days in the previous periods.

After 2004, there was a significant increase in the highest floods. Discharges higher than 40,000 $m^3 s^{-1}$ rarely exceeded a few days when they occurred, except in 1959 (12 days). After 2004, longer durations became more frequent: 9 days in 2004, a historic maximum of 21 days in 2006, and 8 days in 2012. Mean and maximum values underwent a net increase after 2004 (Fig. 7). Whatever the flooding level considered (30,000 or 40,000 $m^3 s^{-1}$), the last decade before 2012 witnessed a major change in the intensity and duration of flood events. The consequences were important: the local population was faced with 40 days of submersion in 2006 (a historical record), 36 days in 2007 and in 2012. However, the Pettitt tests (at the level of significance of 5%) done on the duration data shows that there is no break, probably because the change is too recent.

4.3. Changing temporal distribution

4.3.1. Date of flooding

Two parameters can help identify a possible change: the first day of bar-full level and the date of the flood peak. First, we examined the first day the discharge reached the bar-full level, as this marks the beginning of the flood. The Lena River generally reaches the bar-full level between May 15 and May 25 (Fig. 8). Over the entire period, flooding generally began on May 22 (mean date). In the second half of the 20th century, the probability of flooding before May 15 was rare. The situation clearly changed after 1994 as in several years, flooding began 5–10 days earlier.

Second, detailed analysis of the temporal distribution of the spring flood maximum revealed different phases after 1937 (Fig. 9). For the period as a whole, the mean date of the flood maximum peak was May 30. Early floods (*i.e.* before May 30th) were common before 1973; correlatively, flood peaks were rare in June. After that, the date of the flood maximum was more variable. "Late" rising limbs and peaks (*i.e.* in June) increased. Two late events were also recorded in July, (1988 and 1998). So, the flooding season that was previously expected at the end of May, is now much more unpredictable.

4.3.2. Secondary flood peaks

Rainfall events can create a secondary flood in the summer (August or September). A flood can be actually produced by local intense rainfall or by rainfall in the upstream basin. However, these summer events are exceptional (Table 1). As mentioned above, bar-full and bank-full water levels are rarely observed in late summer and early autumn (August – September, 18 events, Table 1). It would be more accurate to say "were rarely observed": before 1981, water discharge a little above 20,000 $m^3 s^{-1}$ occurred six times, *i.e.* at a frequency of 0.22 time per year; the longest dura-

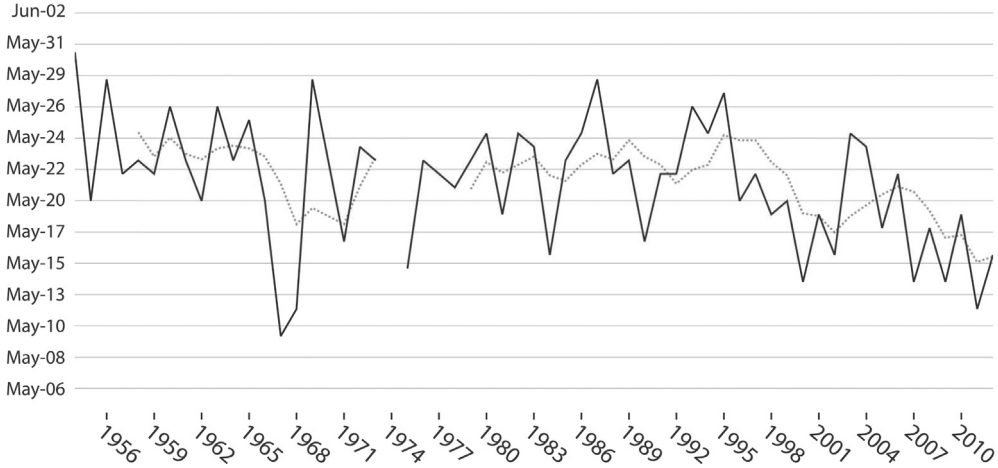

Fig. 8. Date of the first day reaching the bar-full level (1954–2012; dotted line: 5-year-average value).

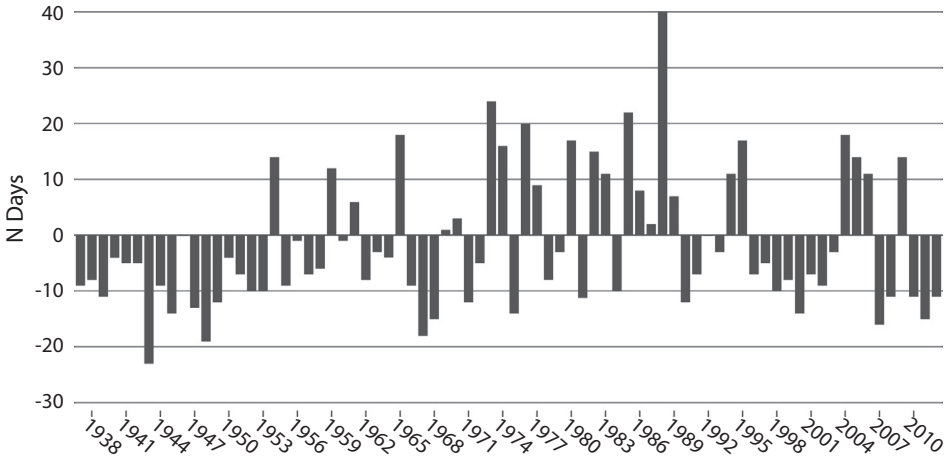

Fig. 9. Date of the flood maximum – Departure from the mean date (0 = May 30).

tions were recorded in September 1959 (12 days), and in September 1973 (16 days). After 1981, the frequency and the intensity of these secondary peaks appear to be increasing: with a frequency of 0.39 time per year, they exceeded 30,000 $m^3 s^{-1}$ three times (Table 1). Furthermore, several overbank flooding events with exceptional peaks were observed at the end of summer: at the end of August and in September 1981, 25 days exceeding 20,000 $m^3 s^{-1}$ were measured, with an exceptional peak at 33,500 $m^3 s^{-1}$ (on September 2). The same observation applies to September 2008 with 16 days above 20,000 $m^3 s^{-1}$ and a peak of 36,700 $m^3 s^{-1}$, in September 2011 with 34,300 $m^3 s^{-1}$ and in August 2012 (38,000 $m^3 s^{-1}$). Thus, these events are more frequent from the beginning of the 21st century.

Recently, secondary peaks that occur in summer or at the beginning of autumn started to occur with unprecedented frequency and intensity (Table 1). "Multi-peak" flooding was observed in several recent years. In 2008, an inversion of the flood hydrograph was observed: the "secondary" peak in September was higher than the spring flood (Fig. 10). Bar-full level lasted 16 days and overbank flow nine. In August 2012, four peaks higher than 30,000 $m^3 s^{-1}$ were recorded.

4.4. High spatial resolution analysis of flooding

The four study years represent a good panel of hydrologic situations in terms of flood intensity, flood date and duration (Table 2). The effect of different hydrologic parameters on river dynamics can be analyzed. Here we report the changes we observed on different islands in the Lena River between 2008 and 2012.

4.4.1. Floods and stream temperature

The gauging station and the thermo-buttons installed on islands in the river provided precise information on flood heights and duration. First, the four-year-study revealed high variability in flood peaks and duration (Table 2). Three floods showed a steep rising limb (2010, 2011, 2012, Fig. 10) with flood peaks between May 15 and May 20. An exceptional breakup occurred in 2010 when discharge reached 51,600 $m^3 s^{-1}$. Although flooding was catastrophic in the area of Yakutsk, it was short (Table 2). Conversely, in 2009 the ice cover melted slowly and the discharge increased progressively and reached maximum in mid-June. The floodplain and islands were flooded for a long time. The year 2011 was dominated by two flood peaks: the first one on May 15 and the second "late" one that was also more than 30,000 $m^3 s^{-1}$ on August 8. In 2012, several peaks exceeding 30,000 $m^3 s^{-1}$ occurred between mid-May and the beginning of August, causing long lasting flooding (more than a month, Table 2). Thus, peak discharge and flooding duration are not necessarily correlated.

The thermo-buttons provided more precise data on the beginning of flooding and its duration on the islands. For example, in 2010 (Fig. 11), flooding began on May 18 (23:00) at a discharge slightly below 30,000 $m^3 s^{-1}$; the water reached a button placed

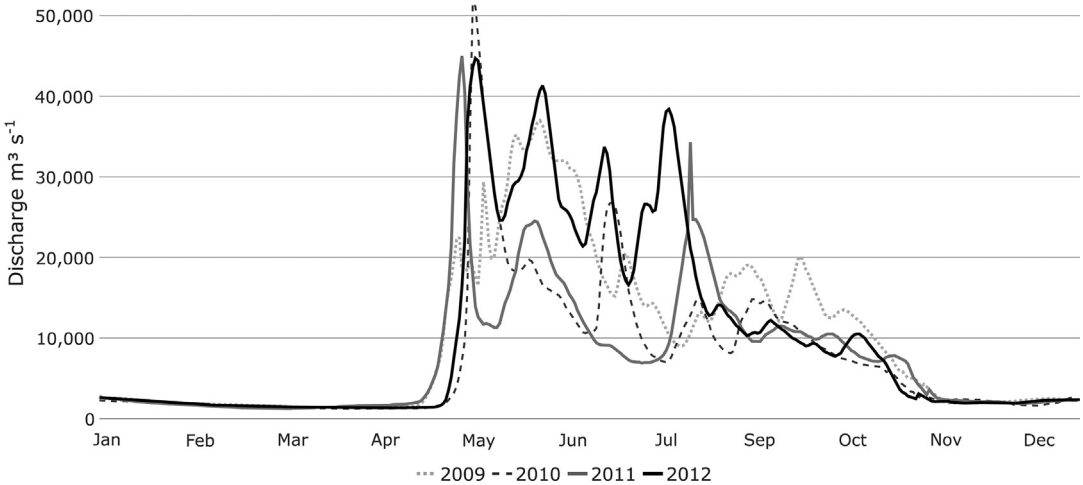

Fig. 10. Recent floods with secondary peaks.

Table 2
Flood characteristics (2009–2012).

	2009	2010	2011	2012
Flood peak ($m^3 s^{-1}$) & Date	37,000 June 14	51,600 May 20	45,000 May 16	44,700 May 20
Total N day >20,000 $m^3 s^{-1}$	45	22	29	79
Total N days >30,000 $m^3 s^{-1}$	25	9	6	30
Total N day>40,000 $m^3 s^{-1}$	0	4	3	8
Mean annual discharge $m^3 s^{-1}$	9722	7318	7467	10 205

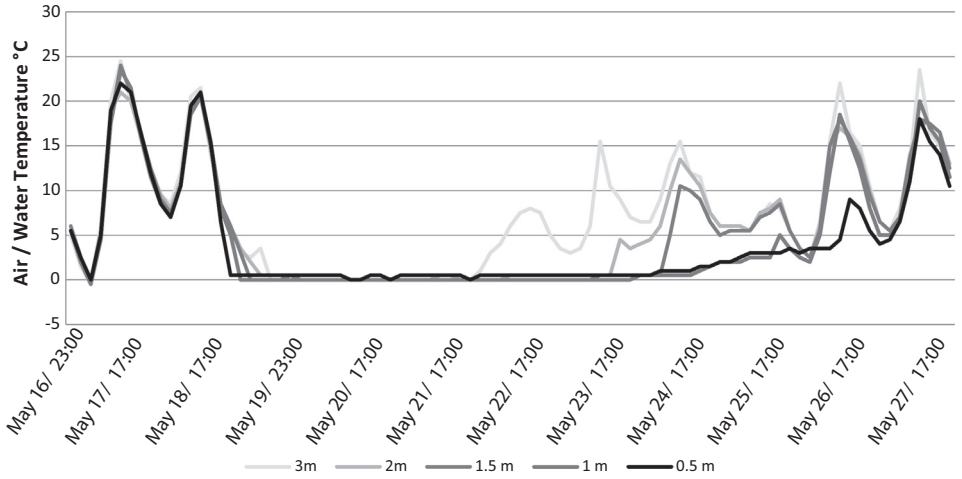

Fig. 11. Beginning and the duration of submersion on Timochka island based on air and water temperature (May 2010). The five thermo buttons were installed at different heights on the same tree. The homogenization of temperature expresses the submersion of the island. The button at a height of 0.5 m shows the beginning (May 18th, 23:00) and the end (May 26th, 14:00) of the submersion and the button at a height of 3 m expresses the maximal water level (submerged from May 19th, 11:00 to May 22nd, 8:00).

at a height of 3 m at 11 a.m. on May 19, confirming the very brutal beak-up which occurred that year. The water level began to go down in the morning on May 22: the emerged button (at a height of 3 m) showed a marked difference with the other buttons that were still submerged. The thermo-button installed 0.5 m from the ground showed flooding ended in the morning on May 26. On Eselyakh Island, we measured the same flood, which began 2–4 h earlier. The two islands were submerged for nine days. During this flood, the water temperature was low (ranging from 0 °C to 2 °C).

The graph of the temperatures measured by the thermo-buttons in 2012 illustrates the increase in water temperature in spring and summer (Fig. 12). During the first phase of the flood (May), the water temperature was 0 °C–1 °C (equivalent to the temperature measured in May 2010). In June, the second peak of flooding submerged the island with warmer water (10 °C–12 °C), and in July, the temperature of the water during the third and fourth flood peaks reached 15 °C and 17 °C, respectively. Thus, the stream temperature strongly increases from the beginning to the end of the flooding season.

5. Discussion

Examination of discharge between 1936 and 2012 confirmed that high variability is an intrinsic feature of the hydrologic functioning of the Lena River and this can be seen at different time scales. A recent historical record of Siberian floods highlights different phases (Myglan and Vaganov, 2011). After a period of hydrologic "calm" (1680–1725), these authors observed more frequent spring floods after 1750 and more frequent summer floods in the

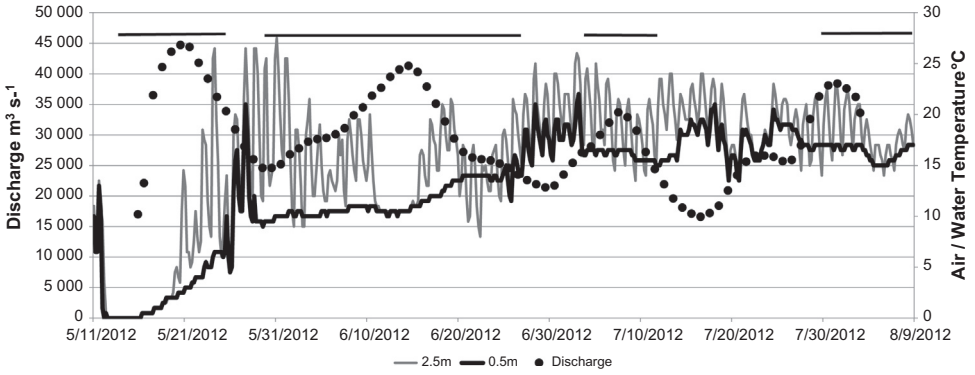

Fig. 12. Changes in temperatures and discharge in May to August 2012. Data from thermo-buttons installed at a height of 0.5 m (dark grey line) and 2.5 m height (paler grey line) on Timochka island. Straight lines indicate the duration of submersion of the island. Dotted line: water discharge.

19th century. On the Lena River, during early floods (on April 27, 1800, for example), a brutal breakup with massive ice dams caused serious damage to villages. Summer floods destroyed pastures, livestock and crops (for example, July 1745, because of heavy rains). "Double peak" events are also feared by local people, for example in May and June 1765 when two flood events were recorded.

According to Rowlands et al. 2010, "permafrost-dominated regions are fundamentally different from their temperate counterparts" (2010: p. 230). In periglacial areas covered by continuous permafrost, winter discharge can be supplied by deep unfrozen water, by a potential talik, or by sub-surface water stored in the channel (French, 1996; Brabets and Walvoord, 2009; Watson et al., 2013; Woo et al., 2008). Ye et al. (2009) established a link between the ratio of maximum to minimum monthly river discharge and the permafrost cover. A high ratio is associated with an extensive permafrost cover (>60% of the basin area). In the middle and lower part of the Lena River basin, where the permafrost is continuous and thick, the maximum/minimum monthly ratio varies between 16 and 48 (Ye et al., 2009). From the middle of the 1980 s to the end of the 1990 s (the data covers the period 1936–1999), the ratio was markedly low, even if no trend emerged. The change was mainly due to the increased minimum river base flow in winter; this change was identified by Yang et al. (2002, 2004). From 1988 to 2004, at Tabaga gauging site, the change affected the monthly minimal discharge (+12% in April). Our study shows that after 2004, both minimum and maximum discharge have been concerned, with respectively +41% in April and +16% in June. When calculating the ratio mean maximal monthly discharge to minimal monthly discharge with additional data (Fig. 13), it clearly demonstrates that the diminishing trend of the ratio is confirmed for the 21st century. Fig. 13 shows a good correlation between the mean air temperature at Yakutsk and the ratio: a cold year generally implies a high ratio and a low ratio corresponds to a warm year. However, since the beginning of the 21st century, high ratios Qmax/Qmin are more likely linked to a net increase of the maximal monthly discharge (in June) that strongly exceeds the increase of the low discharge in April. For example, in 2006, the ratio was very high (40) mainly due to an exceptional monthly discharge in June (43,000 $m^3 s^{-1}$ versus an average value around 24,000 $m^3 s^{-1}$ for 1936–2012).

The same observation concerning the winter base flow was made by Bennett et al. (2015), for the Yukon, Tanana and Nuyakuk Rivers in Alaska, whose basins are dominated by permafrost. Concerning the Yukon River, the increasing discharge in winter and in April reflects a greater supply of groundwater. A general trend showing earlier breakup on the Yukon and Tanana rivers also accompanies the hydrological change (Brabets and Walvoord, 2009). Watson et al. (2013) also confirmed that continuous permafrost controls low winter discharge in small sub-catchments in Eastern and Western Siberia. Concerning the low Lena River at Kusur (near the delta), it has been shown that the cold season (October-April) is affected by a significant increase in stream flow related to winter warming (Yang et al., 2002). However, the low Lena River and the Yenisei basins are mainly influenced by the hydrologic alteration caused by dams and reservoirs (Berezovskaya et al., 2005; Yang et al., 2004), which is not the case in the upper and middle sections of the Lena (present study), as these can be considered as pristine.

Warm season hydrology is governed by different climatic and meteorological processes that act at different time scales. A thicker snow cover accompanied by a warmer winter and/or spring limits penetration of the soil by the cold wave and creates a thicker active layer (Muskett and Romanovsky, 2009; Stieglitz et al., 2003). The thickness of the active layer represents non-negligible groundwater storage. Once again, because of its huge basin, the different sub-catchments of the Lena River react differently to the different parameters. A reduction in the duration of the snow cover has been recorded in the mountains of South Siberia, whereas Central and Eastern Siberia are still subject to longer lasting snow cover (Bulygina et al., 2009). Concerning permafrost, according to Fedorov et al., (2014), the thawing index (sum of positive mean daily air temperature) provides significant information on the dynamics of the permafrost and of the active layer. These authors identified different phases of warming and cooling and reported different reactions in the different regions of Asia. The Central Yakutia was hardly affected by Arctic warming (1935–1945) and during the same period, the thawing index was very slightly positive. This phase was characterized by negative anomalies of the average annual discharge (Fig. 4). The warm phase was followed by a period of cooling (1961–1970) expressed by a negative thawing index. We can underline the fact that the mean annual discharge does not appear to be affected by the cooling phase, as positive anomalies occurred between 1956 and 1963, followed by alternating positive and negative anomalies (Fig. 4). The consequence of the cooling phase could be a slight decrease in the monthly minimal discharge (-8% in April), that could express a reduction in snow cover and delayed snowmelt and ice thawing. No anomaly of the monthly maximum in June occurred during this cooling phase. An increase in the thawing index was evidenced from 1988 to 1995, and the increase was much more pronounced after 2005 (Fedorov et al., 2014). The increased occurrence of early

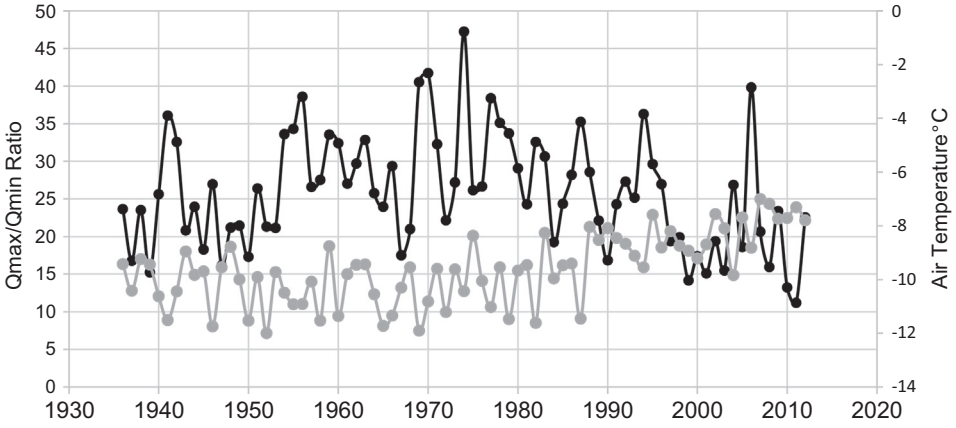

Fig. 13. Relation between discharge ratio and air temperature. In black: maximal to minimal monthly discharge ratio at Tabaga gauging station (ratio defined by Yang et al. 2002) and in grey, air temperature (Yakutsk station).

floods (at the beginning of May, Fig. 6, Fig. 9) could also be explained by the early contribution of snowmelt and ice thawing. Earlier snowmelt and thawing of the active layer (or of the ice covering the river) in spring are expected along the lower 2000-km reach of the Lena River: 4.9–7.5 days earlier in the 2050s and 8.1–13.6 days in the 2080s (Prowse et al., 2010).

Monitoring sites on Siberian plateaus, very close to our study site, clearly revealed an abrupt change in soil temperature and in the depth of the active layer, after 2004 (Iijima et al., 2010; Iijima et al., 2016). Soil moisture content and the depth of the active layer are increasing in parallel (Iijima et al., 2016). According to these authors, moisture and the depth of the active layer are closely linked to summer precipitation (June to September) and to the snow thickness, both factors that have evolved synchronously since the beginning of the 21st century. The combined effect of rainfall in late summer and snow thickness in early winter has a direct impact on soil temperature. The main cause of these recent anomalies is the more frequent and/or more intense advections of storms in Eastern and Central Siberia (Iijima et al., 2016; Overland et al., 2008; Overland and Wang, 2010; Shiklomanov and Lammers, 2009). Before the 2000s, summer rain was usually associated with a cool summer. The association between wet and cool summers was also reported by (Myglan and Vaganov, 2011) for the historical period. In contrast, since the beginning of the 21st century, a wet summer is synonymous with a warm summer (Iijima et al., 2016).

A pluviometric and hydrologic record occurred in 2007 (Shiklomanov and Lammers, 2009), however, the following years far exceeded this ephemeral maximum. Wet years occurred between 2004 and 2008, linked with abnormal storm activity in Eastern Siberia. Precipitation maxima were recorded in Yakutia in 2005 and 2006: more than 200 mm versus an annual average of 150 mm (Iijima et al., 2016). Shiklomanov and Lammers (2009) calculated an exceptional water contribution to the Arctic Ocean in 2007 by six large Russian rivers (including the Lena River): the increased water supply (+25%) occurred in the context of a warmer (+2 °C) and wetter (+100 mm) year. Runoff anomalies were observed particularly in three permafrost-dominated basins, and in parts in the transition between permafrost and non-permafrost areas.

Hydro-climatic conditions over the northern Eurasian continent depend on interactions between Arctic sea ice, pressure centers and the Arctic dipole wind pattern (Serreze et al., 2002; Shiklomanov and Lammers, 2009; Wu et al., 2016; Zhang et al., 2012). The increasing occurrence of cyclones in Northern and Eastern Siberia depends on specific atmospheric fields in Arctic regions in the summer. A surface air temperature associated with sea level pressure creates an anticyclonic situation over North America and a cyclonic situation over north Asia, causing frequent intrusions of storms in Siberia (Inoue and Kikuchi, 2009; Shiklomanov and Lammers, 2009; Iijima et al., 2016). This recent change corresponds to the net increase in river discharge we pointed out: with the exception of 2010 and 2011, all the years after 2005 exceeded the mean annual discharge by more than 30% (Fig. 4), and the duration of flooding was also exceptional in these years. The years 2004 and 2005 thus clearly represent a major transition in the hydrologic dynamics of the middle Lena River.

The recent occurrence of storms in summer and the early autumn is probably the main cause of the "multi-peak" hydrograph we identified in the decade preceding 2012 (Fig. 9 and Fig. 10). It also explains the inversion of the hydrologic year we observed in 2008, with a higher flood peak in September than the "normal" peak in spring.

When comparing the daily discharge data with the air temperature and precipitation data (Yakutsk station), several evidences can be detected concerning the origin of the secondary peaks occurring in summer. We attempted to determine the origin of the secondary peaks. The analysis demonstrates that a wet summer at Yakutsk does not necessarily imply a secondary flood. A "wet" summer is characterized by precipitation above 38 mm in August and 28 mm in September (mean values for 1936–2014). The comparison between hydrologic data and rainfall data shows that a local rainfall triggers a hydrologic response (*i.e.* a discharge increase) when it exceeds at least 80 mm per month. The determination of this rainfall threshold helps identify the main (but not exclusive) origin of a summer flood (Table 1). At Tabaga, there is actually no clear correlation between the occurrence of a secondary flood peak in August or September and the local precipitation. Few floods correspond to local rainfall events. And when a flood peak triggered by a local rainstorm occurs, it is very short (Table 1): in August 2006 a very humid period (151 mm) caused a secondary peak during five days; 2006 being the second wettest year since 1937 at Yakutsk with 326 mm. In 1960, a rainy August (120 mm) created a secondary peak during two days. Thus, the great majority of the secondary summer peaks mainly corresponds to a flood wave coming from the upper basin.

The change in the chronology of the river hydrology deeply can impact the river morphodynamics, not only because of higher and longer floods, but also because of warmer water. The stream temperature of the Lena River depends directly on the air temperature, and the summer stream temperature has increased significantly (Costard et al., 2007;). The thermo buttons measured very warm stream temperatures in June, July and August. One of the most specific processes of periglacial hydrosystems is the thermal-mechanical erosion of their frozen banks (Are, 1983; Costard et al., 2007; Tananaev, 2016). During the high water stage, the permanent contact between the water and the non-cohesive frozen sediment results in rapid bank retreat and in the formation of specific forms such as thermal basal nichas and baydzheraks (Soloviev, 1973; Costard et al. 2014). Longer contact between the "warm" water (up to 15 °C in July as mentioned above) and the bank implies a higher erosion rate. Furthermore, it has been demonstrated that stream temperature is a key factor in thermal erosion. An ablation velocity model constructed on the basis of a mathematical model and on laboratory simulations, revealed that the efficiency of thermal erosion is mainly controlled by the temperature of the water (Costard et al., 2003). Thermal erosion does not necessarily require high discharge to be efficient: bar-full discharge, which enables contact between the base of the bank and the water, is sufficient to destabilize the frozen bank.

6. Conclusion

By reporting on the hydrologic response of the middle Lena River, our study contributes to the demonstration of an "Arctic Warm Period" (Overland et al., 2008; Overland and Wang, 2010).

The concomitance of several hydrologic changes in the two decades preceding 2012 reflects a real change in the dynamics of the middle Lena River. The flood period is being affected in different ways. Spring monthly discharge has undergone a net increase caused by longer bar-full and bank-full water levels. Flood peaks are also more frequent and the date of the beginning of flooding appears to be less predictable. Both earlier and later flood peaks are observed. Late summer secondary peaks are much more frequent and more intense. We assume that the increasing frequency of the secondary peaks is principally linked to more frequent floods originated in the upstream basin. The hydrologic change is not only expressed by the flood intensity but also -and mainly- by the increasing duration of the flood discharges: bank-full and extreme discharges. Furthermore, all changes (mean annual or monthly

discharges, flood magnitude and duration) appear to have been strongly reinforced since the beginning of the 21st century, more precisely, since 2004–2005.

Extreme hydrologic events are a major threat for society (CRED, 2015). Both flooding and low flow have a great effect on human and ecological systems. Even if the projected future impacts of climatic change are subject to strong regional variability and uncertainty, approximately 450 million people who live in floodplains will face double the frequency of flooding in 2050 (Arnell and Gosling, 2016; Arnell and Lloyd-Hughes, 2014). Extreme hydrologic events threaten river infrastructure and navigation, and flood risk management and water resources depend on a good understanding of hydrologic hazards. That is particularly true in Central and Northern Siberia where, even if population density is very low (around 0.3 inhabitants per km^2 in the Sakha Republic), social activities and industry are mainly associated with rivers. The six main cities located on the banks of the Lena River are particularly vulnerable to flooding. The city of Lensk was partly destroyed by the huge flood in 2001. Sudden flooding of the frozen river caused a 16 m rise in the water level and flooded the two thirds of the city. Thousands of people in Lensk were homeless and 1800 homes were destroyed. A large flood of the Angara River also occurred in 2001 (Kichigina, 2013). In May 2010, a historic flood in the region of Yakutsk led to the evacuation of thousands of people: all the villages in the floodplain between Pokrovsk and Kangalassy were submerged.

The efficiency of the water discharges is reinforced by the increase in water temperature: later and longer hydrologic processes are combined with much warmer stream temperatures. Both changes cause more rapid erosion of the frozen banks (Costard et al., 2007; Gautier et al., 2008). The interactions between the duration of discharge and stream temperature affect the stability of the river bed: a higher erosion rate implies an increasing supply of sediments to the river bed. Thus, we assume that the mobility of the channels and islands certainly threatens numerous activities: navigation, and river infrastructure is destabilized or on the contrary, sedimentation increases. These developments will certainly disrupt economic activities in Siberia, which partly depend on the strategic role played by the river, river infrastructure and navigation playing a key role. Rivers are used to transport people, goods, mining resources, and gas and petroleum during the short summer.

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